LIFE AND RELIABILITY ANALYSIS OF C/SIC CERAMIC MATRIX COMPOSITE PANELS SUBJECTED TO COMBINED THERMAL-ACOUSTIC LOADINGS

Yuli Zhang[1], Yi Sun[1*], Xiaojie Chen[1], Yizhi Liu[1] and Song Zhou[1]

[1] Department of Astronautic Science and Mechanics, Harbin Institute of Technology, HARBIN, 150001, CHINA
Email: 14B918021@hit.edu.cn

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ABSTRACT

A study is undertaken to develop a methodology for determining the life and reliability of C/SiC ceramic matrix composite panels subjected to combined thermal-acoustic loadings. Two features of this problem differentiate it from the fatigue of structures subjected to acoustic loading alone. Potentially large mean stresses associated with the thermally pre- and post-buckled states require models capable of handling those conditions. Additionally, snap-through motion between multiple post-buckled equilibrium positions introduces very high alternating stress. A 2D plain-woven C/SiC ceramic matrix composite panel subjected to spatially uniform thermal loading and band-limited Gaussian white noise is chosen as the computational test article, with its geometric nonlinear response determined via numerical simulation. Progressive fatigue damage modeling is employed to simulate the fatigue damage evolution, residual strength and fatigue life of a fully clamped 2D plain-woven C/SiC ceramic matrix composite panel subjected to spatially uniform thermal loading and band-limited Gaussian white noise, with its geometric nonlinear response determined via numerical simulation. The model is an integration of three major components: stress analysis, failure analysis and material property degradation rule. Residual strength is incorporated as fatigue damage accumulation metric. The interaction model (INT) by Harris and co-workers is employed using constant life diagram formulation and different cycle counting methods and fatigue life estimates are made for 2D plain-woven C/SiC using the Tsai-Wu failure criterion. A baseline Palmgren-Miner (PM) damage accumulation rule is additionally considered. Results indicate that a net improvement is achieved when INT strength degradation is implemented as damage metric in life prediction schemes, over the state-of-the-art PM summation. Simulation results confirm the ability of the algorithm to take into account load sequence effects.

1 INTRODUCTION

Future advanced aircraft and aerospace structures will be exposed to increasingly severe operating environments, including a combination of mechanical, pressure, acoustic, and thermal loads. These loading conditions can cause structures to respond in a nonlinear fashion and exhibit complex response characteristics, including snap-through behavior, as evidenced by several numerical[1,2] and experimental[3-5] studies. Acoustic or sonic fatigue, the deterioration of material and structural strength from combined thermal-acoustic loadings, is an important factor in the structural design and safety of modern aircraft and aerospace structures. New materials such as C/C and C/SiC composites have shown themselves to be potentially useful in aircraft structures; however, the limited amount of data related to their performance in the presence of severe operating environments is disturbing to a designer. Thus, analytical techniques for predicting life and reliability when only a minimal amount of material property data is available are urgently needed.

Life prediction in composites under variable amplitude fatigue loading has been a subject of interest for more than three decades now[6]. In contrast to their isotropic counterparts, fatigue modeling and life prediction in composite materials comes up with major difficulties: their inhomogeneous and anisotropic nature causes the formation of various damage mechanisms, from a very early stage of the materials fatigue life. These damage mechanisms depend both on the material and on the loading characteristics, the latter including the cyclic stress level, the fatigue stress ratio and the sequence of load application. This complexity has up to date impeded the development of robust and efficient life prediction methodologies of general acceptance for variety of material systems.

For design methodologies that are based on phenomenological modeling and follow theoretical formulations to eventually estimate the fatigue life under variable amplitude loads, the critical points are the cycle counting algorithm, S-N type selection, a method for extrapolating fatigue life of each cycle from the limited amount of fatigue life data available, and an algorithm for accumulating fatigue damage leading to failure of the laminate.

The most commonly used damage metric in this respect that, however, does not always lead to accurate results, is the well known linear Palmgren-Miner rule. Alternatively, the use of static strength degradation or residual strength, as damage metric in a life prediction scheme appears to be promising. Damage, in that case is expressed by the reduction of static strength of the material during cycling and is directly computed after each cycle of the loading spectrum. The degradation itself depends on various loading parameters such as maximum cyclic load, stress ratio, loading rate etc. In this case, sequence effects are taken into account, since the degradation after each cycle depends on the loading characteristics of the current cycle as well as on the loading history previously experienced by the material.

These models were established, mainly based on data of glass fiber reinforced plastic and carbon fiber reinforced plastic composites loaded under constant amplitude and/or block fatigue loading. The last 30 years has seen intensive research efforts devoted to the study of fatigue behavior of glass fiber reinforced materials under variable amplitude fatigue loading. Several researchers have reported test data and theoretical predictions of damage from variable amplitude fatigue loading, mainly using the standardized spectra for wind turbine rotor blades, WISPER and WISPERX. Both conservative and non-conservative predictions were presented[7].

This paper examines the structural properties and fatigue life of C/SiC Ceramic Matrix Composite panels in a thermal-acoustic environment. Based on progressive fatigue damage modeling, a computer code is developed that simulates cycle-by-cycle behavior of composite laminates under fatigue loading. As the input, the material properties (static strength, residual strength and fatigue life) of this material are fully characterized under tensile and compression, for fiber direction at elevated temperature in static and fatigue loading conditions. Once the typical fatigue and static properties of this material are determined, the fatigue behavior and residual strength can be simulated.

2 THERMAL-ACOUSTIC NONLINEAR RESPONSE ANALYSIS

A 2D plain-woven C/SiC ceramic matrix composite panel served as the basis for the current investigation. The panel measured 288mm × 288mm × 2mm, and had clamped boundary conditions at all ends. The material properties at temperature 137°C are given with elastic modulus E1=120GPa, E2=E3=60GPa, shear modulus G12=44.4GPa, G13=G23=24GPa, mass density ρ=2100kg/m^3, and coefficient of thermal expansion α11=α22=4×10^{-7}/°C, α33=1×10^{-6}/°C. Material properties were assumed to be temperature independent because of the modest temperature range considered in this paper.

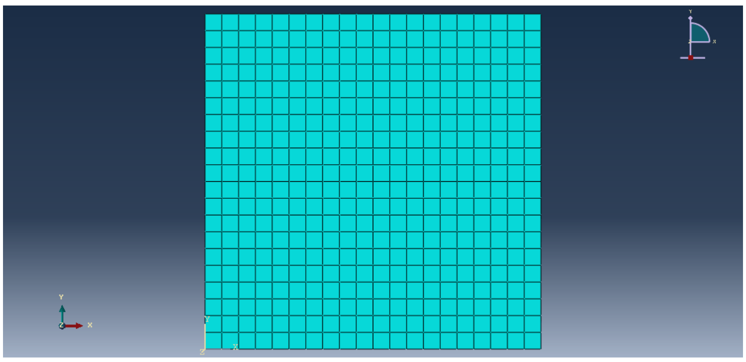


Figure 1: The finite element model.

The panel response was analyzed with the finite element code ABAQUS. The finite element model consisted of 400 S4R Shell elements, see Fig. 1. The ABAQUS/Explicit solution was used with an automatic time step adjustment, known as 'element-by-element' in ABAQUS. This approach yields a conservative time step increment.

The panel is simultaneously subjected to a stationary band-limited Gaussian white noise pressure uniformly distributed over the panel surface and a spatially uniform time-invariant thermal loading having zero through-thickness variation. The white noise pressure time history is generated by inverse fast Fourier transform method that simulates a random pressure using complex numbers with independent random phase angles uniformly distributed between 0 and 2π[1]. The analyses presented are obtained for a cut-off frequency of 512 Hz, and three sound pressure levels (SPL, 116 dB, 120 dB and 130 dB) are considered. The corresponding overall sound pressure levels (OASPL) are 146.1 dB, 150.1 dB and 160.1 dB, respectively. The random pressure time history is 2s in duration involving 2^{14}=16384 time steps. A typical simulated random pressure loading is shown in Fig. 2. Two studies for accurate and converged response predictions were performed. They are the finite element mesh sizes and the integration time steps.

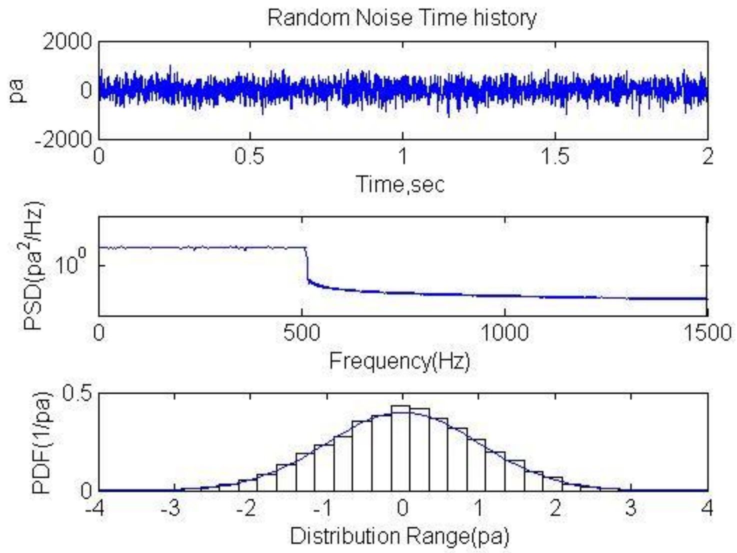
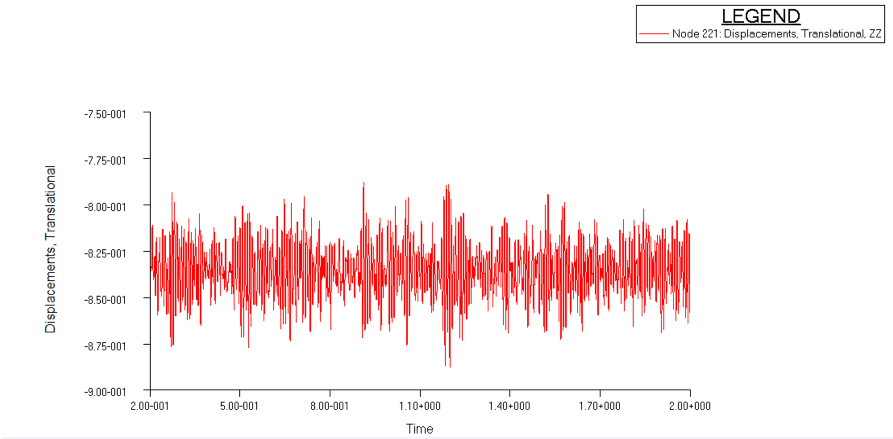
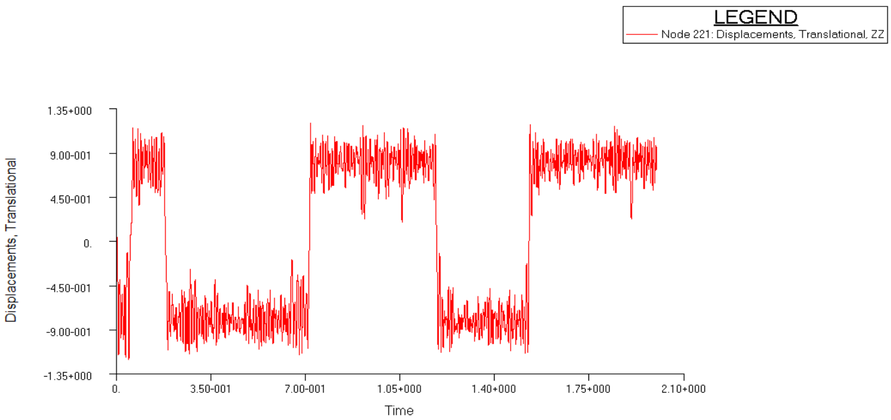


Figure 2: Random noise loading of generation (116dB).

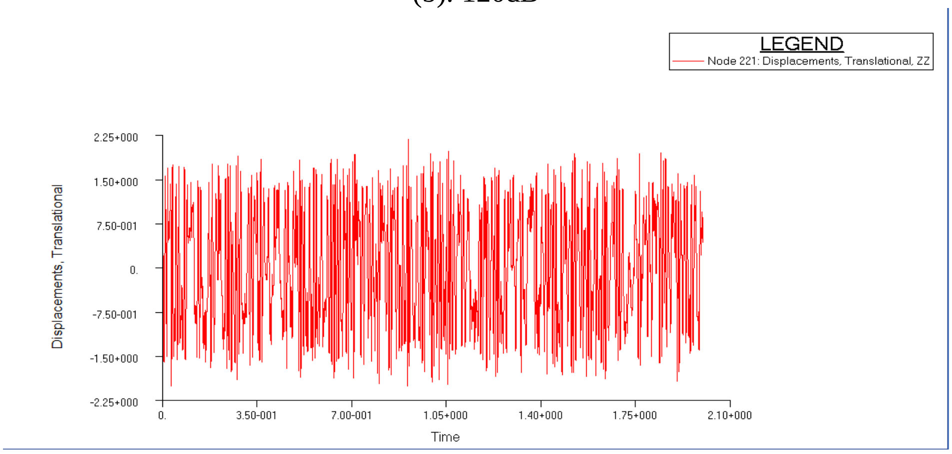
In order to study the snap-through response, three thermal loadings are considered. A room temperature (T=27 ℃, ΔT=0 ℃) condition is assumed as an unstressed reference, the critical bucking temperature increment of the panel is T_C=137 ℃. T=130 ℃ is chosen to study the thermally pre-buckled response. For both the conditions, there exists a unique neutral equilibrium position, and no snap-through response is expected under any acoustic loading level. To investigate the snap-through response, a temperature increment of 140 ℃ is used. For this condition, with the increase of the acoustic loading level, three different types of panel motions can be predicted: (1) random vibration about one of the buckled equilibrium position, (2) snap-through motions between the two buckled equilibrium positions (intermittent snap-through) and (3) snap-through motions over the two buckled equilibrium positions (persistent snap-through).



(a). 116dB

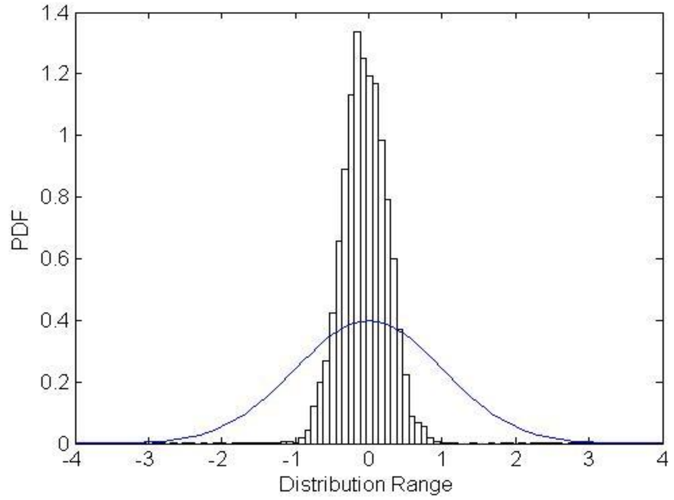


(b). 120dB

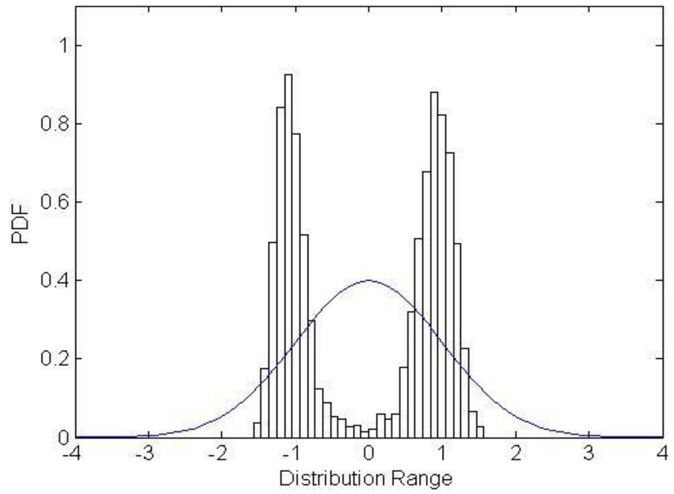


(c). 130dB

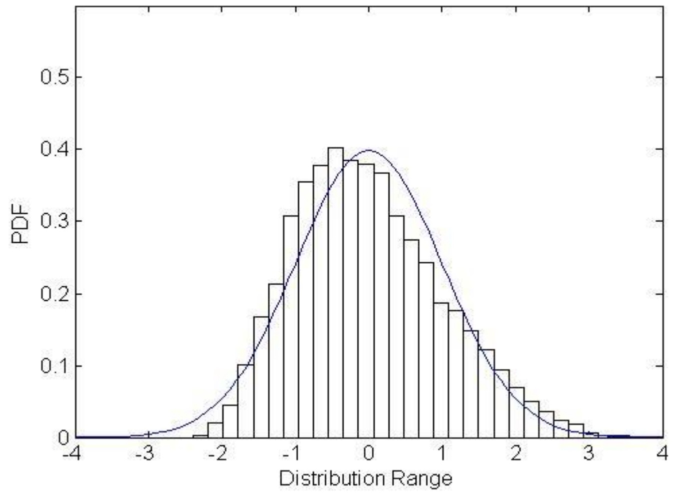
Figure 3: Transverse displacement response at the center of the thermally post-bucked panel



(a). 116dB



(b). 120dB



(c). 130dB

Figure 4: PDF of the transverse displacement response at the center of the thermally post-bucked panel

The time histories and probability density function (PDF) of transverse displacement at the panel center for T=140 ℃ are shown in Figs. 3 and 4, respectively. As can be seen, at low 116 dB and T=140 ℃, the time histories in Fig. 3(a) clearly shows the linear random responses about one of the thermally buckled equilibrium position, and the PDF plot in Fig. 4(a) shows the response is a Gaussian process. As the SPL increased to 120 dB in Figs. 3(b) and 4(b), the intermittent snap-through is observed and the displacement PDF is non-Gaussian. At high SPL of 130 dB in Figs. 3(c) and 4(c), the larger displacement covers both buckled positions, and nonlinearity is also observed from the PDF of transverse displacement.

3 PROGRESSIVE DAMAGE MODELLING UNDER SPECTRUM LOADING

Progressive damage modelling is a simple but efficient way, which accounts for the fatigue damage modes developing due to the complex stresses induced under constant or variable amplitude fatigue loading. The algorithm can be divided into four main modules: (1) stress analysis, (2) determination of fatigue life under arbitrary cyclic load, (3) gradual residual strength degradation rules and (4) final failure definition.

3.1 Stress analysis

Linear elasticity is assumed for the stress-strain constitutive equations. Even though this assumption is quite accurate for the fibre direction, it is not so for the in-plane shear of 2D plain-woven C/SiC. Nevertheless this approximation appears reasonable during the development of an engineering oriented application. Out of plane shear and through the thickness stresses are not considered.

3.2 Cycle counting methods

Cycle counting is used to summarize irregular load-versus-time histories by providing the number of occurrences of cycles of various sizes. Several methods for counting cycles during variable amplitude fatigue have been established in the literature, varying from simple counting concepts to more sophisticated algorithms. Some of the former are the peak, level crossing or simple range-mean counting algorithms, while the latter includes routines under the general title of Rainflow counting[8].

While the use of a Rainflow method produces correct cycles in terms of stress–strain events, the spectrum is inevitably rearranged, since peaks and troughs even from distant sections are combined to produce full cycles. This fact possibly leads to neglecting sequence effects that could play a significant role in fatigue life of composites. In the present study a basic investigation of the effect of counting method is attempted: On one hand the simple range-mean Counting method and on the other a Rainflow method is implemented, which however, does not group the cycles but retains their order as they arise during the progression of the algorithm.

3.3 Constant life diagrams

Constant life diagrams (CLDs) are used in fatigue analysis in order to take into account the effect of mean stress on the fatigue behavior of composite materials. They provide a mean for the theoretical calculation of S–N curves under, virtually, any constant loading pattern. In the investigation[9] it was indicated that a detailed experimental characterization including many S-N curves would probably result in improved spectrum life predictions. On the other hand, the diagram in this region is distorted by the questionable assumption that all CLD lines converge to the UTS and UCS when $R\rightarrow1$. Consequently, special attention should be paid in accurately modelling the fatigue life between $R = 0$ and $R = 1$ as well as between $R = \pm\infty$ and $R = 1$. In the frame of this work, unknown S–N curves are calculated by linear interpolation between known values of fatigue and static strength data. Nevertheless, other type of interpolation scheme could be potentially used to produce eventually more accurate diagrams.

3.4 Residual strength degradation

The fatigue damage accumulation metric implemented in the algorithm is based on residual strength degradation. Residual tensile and compressive strengths are considered while each residual strength component is treated as a function of the cyclic stress parameters on the same direction. Since the assumption of linear degradation of static strength proves to be conservative, especially for high cycle fatigue, when compared to experimental data, a nonlinear model is used to better describe the phenomenon. A variety of such models has been published in the past, the model implemented herein is the interaction model (INT) by Harris and co-workers[10], which can vary in shape from linear to circular arc to extremely angular depending on the parameters. Thus, this model can accommodate both gradual wear-out and sudden-death type behavior. It is based on the following degradation equation:

$$t^{\alpha}+r^{\beta}=1 \text{ where } t=\frac{\log n-\log 0.5}{\log N-\log 0.5} \text{ and } r=\frac{S_r-\sigma_p}{S_u-\sigma_p} \tag{1}$$

Harris et al. describe several methods of calculating the error between experimental data and this curve in order to optimize the fit of α and β. Having determined α and β from a master curve, the residual strength is evaluated as

$$S_r=\left(S_u-\sigma_p\right)\left[1-\left(\frac{\log n-\log 0.5}{\log N-\log 0.5}\right)^{\alpha}\right]^{1/\beta}+\sigma_p \tag{2}$$

This empirical model that appears to work well to collapse residual strength curves at different stress levels. Although Harris et al. did not apply their model to spectrum loading, the extension is obvious if we assume that residual strength must be a continuous function of cycles:

$$S_r\left(i\right)=\left(S_u-\sigma_{p,i}\right)\left[1-\left(\frac{\log\left(n_i+n_{eqv,i-1}\right)-\log 0.5}{\log N_i-\log 0.5}\right)^{\alpha}\right]^{1/\beta}+\sigma_{p,i} \tag{3}$$

$$\log n_{eqv,i-1}=\left(\log N_i-\log 0.5\right)\left[1-\left(\frac{S_{r,i-1}-\sigma_{p,i}}{S_u-\sigma_{p,i}}\right)^{\beta}\right]^{1/\alpha}+\log 0.5 \tag{4}$$

3.5 Failure criterion

Predictive formulations of the fatigue life of composite materials that take stress multiaxiality into account appeared in the 1970s. Most of the proposed criteria were generalizations of static criteria in order to consider fatigue parameters, like number of cycles to failure, frequency, stress ratio etc. Both uniaxial and multiaxial fatigue experiments were performed in order to assist the development of the fatigue theories and evaluate their predictive ability. A review[11] of multiaxial fatigue theories for composite laminates has recently been presented by Quaresimin et al., in which the authors concluded that, although some of the existing theories are accurate, they cannot always guarantee a safe fatigue design under any loading condition. However, the fairly simple formulation of some of the criteria and the straightforward method of application make them attractive for design procedures and implementation in numerical codes. Thus, the failure criterion developed by Tsai-Wu is generalized for fatigue loading and implemented in the algorithm, as well as the baseline Palmgren-Miner rule.

4 EXPERIMENTS

An extensive experimental program on a C/SiC material has been performed in order to support research and advance the knowledge on the behaviour of such materials. All tests used in the present work consist of the static strength, fatigue life and residual strength tests, performed for the characterization of the 2D plain-woven C/SiC in its principal directions, in order to provide the necessary input to the simulation algorithm.

Fatigue data were processed statistically and S-N curves at 50% reliability level were used to compare with experimental data in the present work. Parameter values of the fatigue functions, in the form (5) used in the calculations to derive the results reported herein and INT model along with the respective static strength values are summarized in Table 1.

$$\log N = a \log \left\| \sigma_p \right\| + b \tag{5}$$

S_{uts}(MPa)	S_{ucs}(MPa)	R	a	b	α	β
196.71	-266.45	0.1	-9.99	28.54	11.72	6.20
		10	-18.02	29.68	7.48	4.99

Table 1: Static strength and the parameter values of power law S-N curve and INT model for C/SiC

5 REDULTS AND DISCUSSION

When numerical calculations were carried out to predict the fatigue life, the transient response must be eliminated to ensure the proper response statistics are recovered. For each loading history, the first 0.2s was discarded. The stress time histories are processed in the course of fatigue post-processing, and then, a computer code for the interaction residual strength model and Palmgren-Miner rule was written using a standard programming language MATLAB to predict the fatigue life of panel subjected to combined thermal-acoustic loadings. Fatigue life estimates at the panel center are considered, since the stresses there are highest and will dictate the fatigue life of the structure as a whole.

Fig. 5 shows the fatigue life prediction of the interaction residual strength model with Palmgren-Miner rule under different acoustic loading. It can be seen that at a given thermal loading, the fatigue life decreases rapidly with the increase of SPL. It has to be mentioned here that the dashed lines are used to emphasize the change trends in this plot of fatigue life versus SPL. It is not valid to interpolate along these lines to obtain intermediate values.

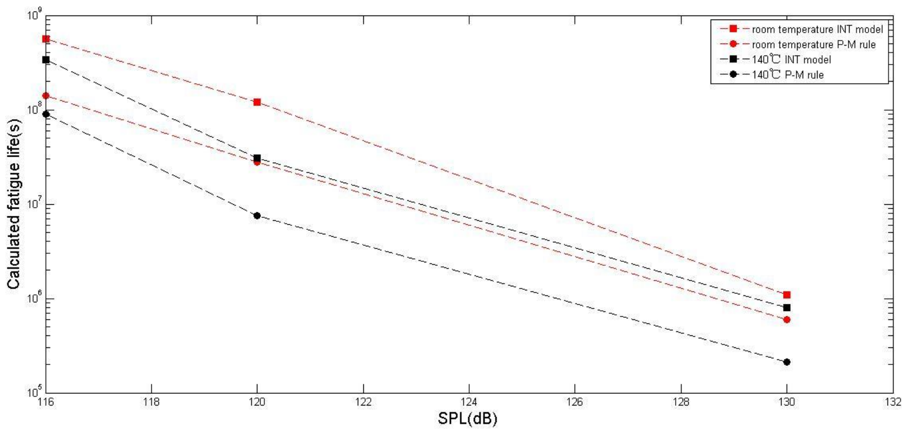


Figure 5: The fatigue life of center for the three acoustic loading at given thermal loading.

6 CONCLUSIONS

A simple life prediction scheme for C/SiC ceramic matrix composite panels subjected to combined thermal-acoustic loadings has been presented in detail herein. The model is an integration of three major components: stress analysis, failure analysis and material property degradation rule. Residual strength is incorporated as fatigue damage accumulation metric. The interaction model (INT) by Harris and co-workers is employed using constant life diagram formulation and different cycle counting methods and fatigue life estimates are made for 2D plain-woven C/SiC using the Tsai-Wu failure criterion. A baseline Palmgren-Miner (PM) damage accumulation rule is additionally considered. Results indicate that a net improvement is achieved when INT strength degradation is implemented as damage metric in life prediction schemes, over the state-of-the-art PM summation. Simulation results confirm the ability of the algorithm to take into account load sequence effects.

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